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(54) Title: LOW REFLECTIVITY FIBER BRAGG GRATING WITH RECTANGULAR REFLECTION FUNCTION

(57) Abstract

Fiber Bragg gratings of low reflectivity are given a squared reflectivity function in the form of a tophat configuration having a flat top and lacking undesirable side lobes (12). Such a reflectivity function for a fiber Bragg grating is achieved by interfering a diffracted beam (20) with a plane wavefront beam so as to impose a sinc function on the resulting interference pattern that imprints the grating on an optical fiber (10).

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LOW REFLECTIVITY FIBER BRAGG GRATING WITH RECTANGULAR REFLECTION FUNCTION

Field of the Invention

5   The invention occurs in the field of fiber Bragg gratings formed in optical waveguides by exposing a photosensitive waveguide core to an interference pattern formed by overlapping beams of actinic radiation.

Background

10   Fiber Bragg gratings for reflecting (or transmitting) wavelengths of light within optical waveguides are known to have reflectance functions that suffer from undesirable side lobes when the grating has a constant coupling strength along its length. Such side lobes are especially

15   undesirable for narrow band and dense wavelength division multiplexing. Problems with such side lobes and attempts at eliminating such side lobes have been discussed in U. S. Patents 5,309,260 and 5,388,173, for example.

20   For many purposes, the optimum reflectance function for a fiber Bragg grating is a three-sided rectangle, with a flat top and nearly vertical sides in a "tophat" configuration. Prior art suggestions for different ways of making fiber Bragg gratings have so far failed to achieve

25   this.

Summary of the Invention

For low reflectivity gratings, the desired tophat

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configuration for the reflectivity function of a fiber
Bragg grating can be closely approximated by making the
envelope function of the grating a sinc function. A sinc
function for the envelope function of the grating can be
5   achieved by interfering two angled writing beams, one of
which has a plane wavefront and another of which is
diffracted. The diffracted beam is preferably diffracted
through a slit oriented transverse to the fiber and then
propagated to the far field where it interferes with a
10   plane wavefront beam in an interference pattern incident on
the fiber core. The plane wavefront beam is preferably at
least twice the intensity of the diffracted beam. This way
of imposing a sinc function on the envelope function of the
grating causes the grating phase to change by π every time
15   the sinc function passes through zero, which helps the
reflectivity function of the grating approximate the
desired tophat configuration.

                          Drawings
20   Figure 1 is a schematic view of a preferred
arrangement of overlapping, actinic writing beams
interfered in a pattern to form a grating on an optical
fiber.
            Figure 2 graphically represents a sinc function shown
25   as the amplitude of the diffracted beam in the arrangement
of FIG. 1.
            Figure 3 graphically represents the intensity of the
sinc function beam of FIG. 2.
            Figure 4 graphically represents the resultant
30   amplitude of the interference of the diffracted beam and
the plane wave beam of FIG. 1.
            Figure 5 graphically represents the intensity of the
interference pattern of the overlapping beams of FIG. 1.
            Figures 6-9 graphically represent spectral
35   reflectivities of gratings made by using different numbers

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of lobes on each side of the central peak of the sinc - function of FIG. 2.

Figures 10-13 graphically represent spectral reflectivities of gratings using six lobes of the sinc function of FIG. 2 and using different values for delta n.

Detailed Description

This invention arises from the discovery that a sinc function imposed on the grating envelope of a fiber Bragg grating allows the spectral reflectivity function of the grating to approach a desired tophat configuration, with nearly vertical sides and a flat top. It also involves recognition of a simple and effective way that such a sinc function can be imposed on the grating envelope to achieve the desired tophat reflectivity. A way of making the inventive grating will be described first. Then, the reflectivity characteristics of the inventive grating and the underlying mathematics will be explained.

To form a fiber Bragg grating with a spectral reflectivity in a tophat shape, two angled beams of actinic radiation are overlapped in an interference pattern incident on a photosensitive waveguide. One of the beams preferably has a plane wavefront, and the other beam is preferably diffracted to impose a sinc function on the interference pattern that defines the grating envelope. Much of the technology for accomplishing this is well understood in the art. Photosensitive cores for waveguides such as optical fibers can be made so that their index of refraction is varied in response to a pattern of actinic radiation, such as UV light. The time and intensity of the exposure, and the configuration of the interference pattern, determine the pattern of index variation imprinted on the fiber core by the writing beams. Various beam arrangements and pattern configurations for forming fiber Bragg gratings have been suggested.

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In the preferred arrangement of FIG. 1, a fiber 10 having a photosensitive core is imprinted with a grating pattern corresponding to the interference of a pair of overlapping beams 15 and 20. These are preferably derived

5   from a single source 11 of actinic radiation, such as UV light. A beam 12 from source 11 is divided by beamsplitter 13 into a primary beam 15 and a secondary beam 16. Primary beam 15 preferably has a plane

10   wavefront, and optical elements that are not shown in FIG. 1 can be used to accomplish this.

Secondary beam 16 is directed by mirrors 17 and 18 to an orientation angled relative to primary beam 15. Then, beam 16 is directed by mirror 18 through a narrow

15   diffraction slit 19 oriented transversely or perpendicular to fiber 10. Beam 20 passing through slit 19 is diffracted and propagated to the far field where it interferes with primary beam 15 in overlapping incidence on fiber 10.

Diffracted beam 20 imposes the desired sinc function

20   on the interference pattern created with beam 15. This in turn imposes the sinc function on the envelope function of the grating's pattern of varying index of refraction as imprinted in fiber 10. This changes the phase of the grating by π every time the sinc function passes through

25   zero, and it gives the grating a reflectivity function in the desired tophat form. As explained below, the Fourier transform of a reflectivity function in the desired tophat shape is a sinc function, which the diffracted beam imposes on the grating envelope for a low reflectance grating.

30   FIG. 2 shows the sinc function form of the amplitude of diffracted beam 20. Diminishing side lobes appear on each side of a central amplitude peak, and the amplitude passes through zero twice for each side lobe.

The intensity of the sinc function beam 20 is shown in

35   FIG. 3 and is obtained by squaring the amplitude of FIG. 2.

5

The intensity is a measurable quantity.

The amplitude that results when diffracted beam 20 interferes with plane wave beam 15 at fiber 10 is shown in FIG. 4. This also shows the π phase change at each zero crossing.

The intensity of the interference pattern formed by overlapping beams 15 and 20 is shown in FIG. 5. This intensity is obtained by squaring the data of FIG. 4, and it corresponds to the changes in the index of refraction of the interference pattern imprinted on fiber 10. The sinc function imposed on this pattern produces the tophat approximation for the reflectivity of the grating.

Calculated reflectivities for gratings made with sinc function envelopes as described above are shown in FIGS. 6-13. Different numbers of side lobes of the sinc function of beam 20 can be used by selectively masking the edges of beam 20. The reflectivity resulting from use of a single side lobe on each side of the central peak of the sinc function of FIG. 2 is shown in FIG. 6. The sides of the reflectivity function have noticeable slopes, and the top is not ideally flat. Increasing the number of side lobes of the sinc function to three lobes on each side of the central peak produces the improved reflectivity shown in FIG. 7. Successively closer approximations to the desired tophat configuration can be achieved by using increasing numbers of side lobes of the sinc function, as is apparent from FIG. 8 showing use of 6 side lobes on each side of a central peak, and from FIG. 9 showing use of 12 sides lobes on each side of a central peak.

FIGS. 10-13 show the calculated reflectivity spectrum effects of increasing reflectivity of the grating. The reflectivity is increased by increasing delta n which can be done by increasing the time and/or intensity of the exposure of fiber 10 to actinic light. The calculations for FIGS. 10-13 use six lobes on each side of a central

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peak for the sinc function. They show a good approximation -
to a tophat configuration for low reflectivities such as
about 7 percent in FIG. 10, about 18 percent in FIG. 11,
and about 50 percent in FIG. 12. At higher reflectivities,
5   the desired tophat shape for the reflectivity spectrum
begins to deteriorate. A 90 percent reflectivity, as shown
for example in FIG. 13, has noticeably sloping sides.

The mathematics behind the graphic representations of
FIGS. 2-13 are as follows:
10   The index distribution n, for a fiber phase grating is
expressible as:

$$n = n_{oo} + \Delta n[1 + f(z)\cos(Kz)]$$

where: n_{oo} is a refractive index of a core of the
waveguide,
15   Δn is an induced difference in the refractive index
of the core,
$f(z)$ is an envelope function of the grating, and
$K = \frac{2\pi}{\Lambda}$ is a grating wave vector for a grating period Λ.
20

For small reflectivities, of less than about 50 percent
reflectivity, as shown in FIGS. 10-12, the reflection
function of the grating is the Fourier transform of its
25   envelope function $f(z)$. Since the Fourier transform of the
desired rectangular tophat configuration for the reflection
function is a sinc function; $f(z)$ is preferably a sinc
function to make the grating produce the desired result.
Such a sinc function is obtained as previously explained by
30   interfering a plane beam and a diffracted beam, and
preferably a diffracted beam that is diffracted through a
narrow slit oriented transversely to a fiber being
imprinted.

The length of each grating depends on the desired
35   bandwidth and the number of lobes included in the sinc
pattern. It is usually several millimeters and can be up
to about 10 mm. Gratings performing according to the

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calculated graphic results of FIGS. 6-13 can be achieved
with the following typical parameters:

Length ≥ 1 cm

n_{∞} = 1.444

5   Λ = 0.5365 mm

Δn = 0.0005

$$f(z)=sinc(Az)= \frac{sin(Az)}{(Az)}$$

with A = 0.015

10   The term A is related to the spectral width of the
reflection spectrum, Δλ , by: $\Delta\lambda = \frac{A\lambda^2}{2\pi n}$

15   where λ is the center wavelength of the filter and n
is the effective index of the waveguide.

The diffracted beam 20 is preferably propagated to the
far field before interfering with plane wavefront beam 15,
and the far field is given as:

20

$$[z>>(\pi)]\frac{r^2}{2}$$

where:

25   z is the distance from the aperture to the
interference plane,

λ is the wavelength of the light, and

r is the width of the diffraction slit.

The angle between the two beams 15 and 20 is
30 selected to obtain the desired center wavelength (Bragg
matched wavelength) of the grating. This angle is
affected by the wavelength of the beams, which is
typically 240 nanometers.

Bragg wavelength $= \frac{2n\lambda}{2 \sin theta}$

35

where theta is the half-angle between the
writing beams.

8

This yields values for angles between the writing beams of typically 26 degrees, and such angles are preferably variable so that gratings can be imprinted with the desired center wavelength for the reflectivity function.

5

The plane wave beam 15 preferably has at least twice the amplitude of the diffracted beam 20. A more intense plane beam 15 improves the approximation of the grating's reflectivity function to the desired tophat form.

10

There may be other ways of diffracting beam 20 to give it a sinc function form. Edge diffraction is one possibility.

9

WE CLAIM:

1.   A fiber Bragg grating having a core patterned
with a varied index of refraction corresponding to varied
intensities of an interference pattern of actinic
radiation incident on the fiber core from interference of
a plane wavefront beam and a diffracted beam.

2.   The grating of claim 1 wherein the reflectivity
of the grating is up to about 50 percent.

3.   The grating of claim 1 wherein the length of
the grating is from 1 to about 10 mm.

4.   The grating of claim 1 wherein the diffracted
beam is diffracted through a slit oriented transverse to
the fiber.

5.   The grating of claim 1 wherein the beams are
derived from a single source.

6.   The grating of claim 1 wherein the angle
between the beams is selected to obtain a desired center
wavelength of reflection of the grating.

7.   The grating of claim 1 wherein the plane
wavefront beam has at least twice the intensity of the
diffracted beam.

8.   The grating of claim 1 wherein the diffracted
beam is arranged to apply a sinc function to the envelope
function of the grating.

9.   A method of making a fiber Bragg grating having
a core patterned with a varied index of refraction, said
method comprising:

   a.   providing a fiber having a core that can be
         patterned by actinic radiation;

   b.   arranging angled beams of actinic radiation to
         form an interference pattern incident on the
         fiber core;

   c.   arranging a first one of the beams to have a
         plane wavefront; and

   d.   arranging a second one of the beams to be

10

diffracted..

10.   The method of claim 9 including arranging the
interference pattern to extend over at least one
5   centimeter of the length of the fiber core.

11.   The method of claim 9 including diffracting the
second beam through a slit transverse to the fiber.

12.   The method of claim 9 including arranging the
plane wave beam to have at least twice the intensity of
10   the diffracted beam.

13.   The method of claim 9 including arranging an
angle between the beams to obtain a desired center
wavelength of reflection of the grating.

14.   The method of claim 9 including deriving the
15   beams from a single source.

15.   The method of claim 9 including diffracting the
second beam to apply a sinc function to the envelope
function of the grating.

16.   A fiber Bragg grating having a refractive index
20   distribution, n , expressible as:

$$n = n_{\infty} + \Delta n [1 + f(z) \cos (Kz)]$$

where: n_{∞} is a refractive index of a core of the
grating,

Δn is an induced difference in the refractive index
25   of the core,

$f(z)$ is an envelope function of the grating, and

$K = \dfrac{2\pi}{\Lambda}$ is a grating wave vector for a grating period Λ,

5

    the grating comprising: the envelope function $f(z)$ being a sinc function, and the sinc function being obtained by interfering a plane wavefront beam with a diffracted beam.

10   17. The grating of claim 16 wherein the sinc function is expressed as:

$$f(z) = \text{sinc}(Az) = \frac{\sin(Az)}{(Az)}$$

15   where: A is related to a spectral width of a reflection spectrum, $\Delta\lambda$, of the grating by:

$$\Delta\lambda = \frac{A\lambda^2}{2\pi n}$$

20   18. The grating of claim 16 wherein the reflectivity of the grating is up to about 50 percent.

    19. The grating of claim 16 wherein the ~~length of the grating is~~ from 1 to about 10 mm.

    20. The grating of claim 16 wherein the
25 diffracted beam is diffracted through a slit oriented transverse to the fiber.

    21. The grating of claim 16 wherein an angle

12

between the plane wavefront beam and the diffracted beam
is selected to obtain a desired center wavelength of
reflection of the grating.

5   22.   The grating of claim 16 wherein the plane
wavefront beam has at least twice the intensity of the
diffracted beam.

      23.   The grating of claim 16 wherein the plane
wavefront beam and the diffracted beam are derived from a
single source.
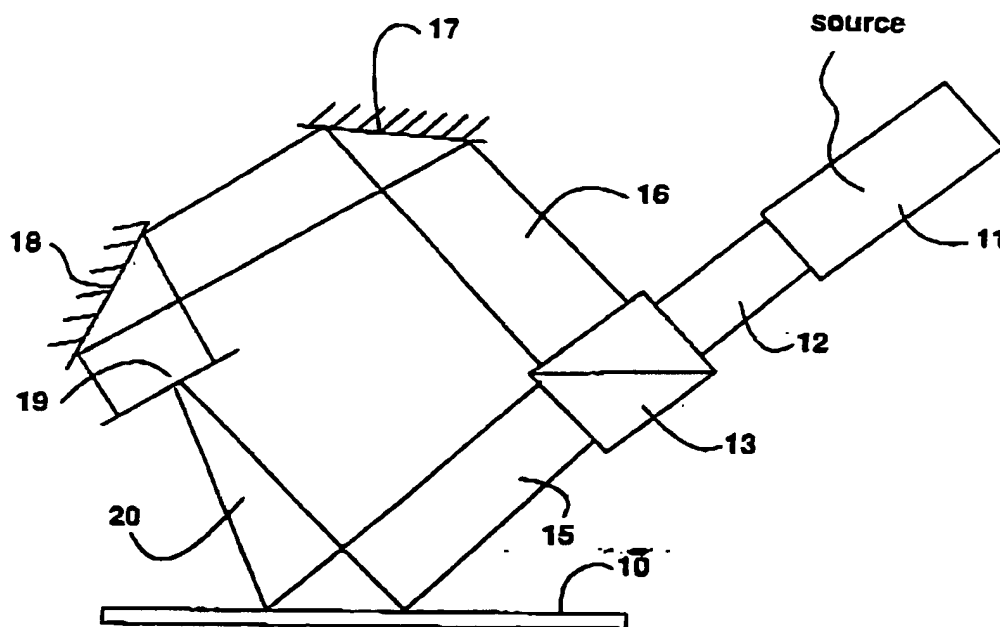
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FIG.1

FIG.2

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FIG.3

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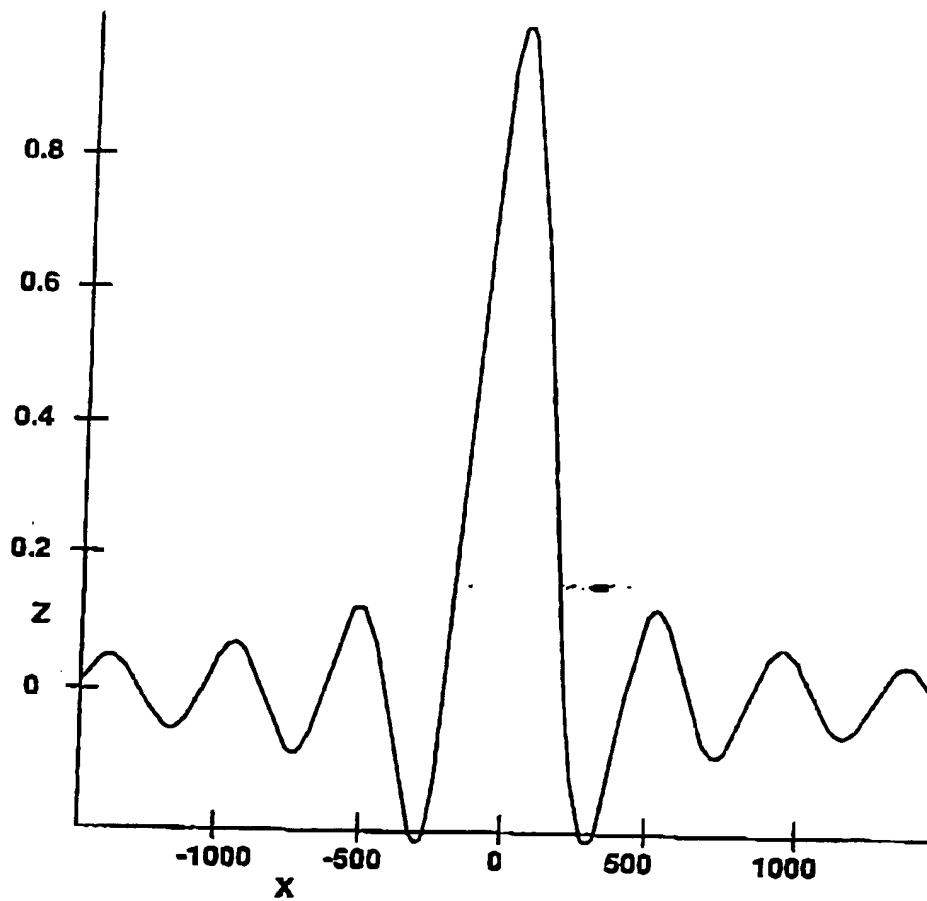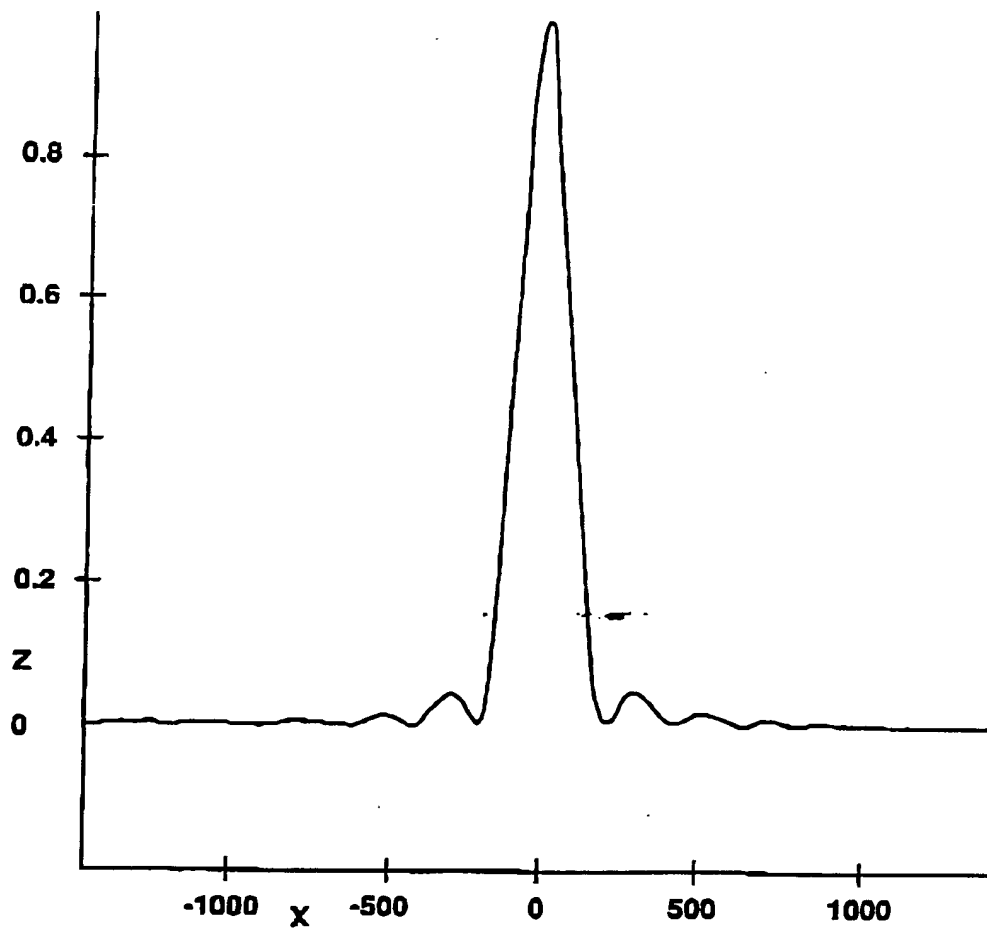
FIG.4
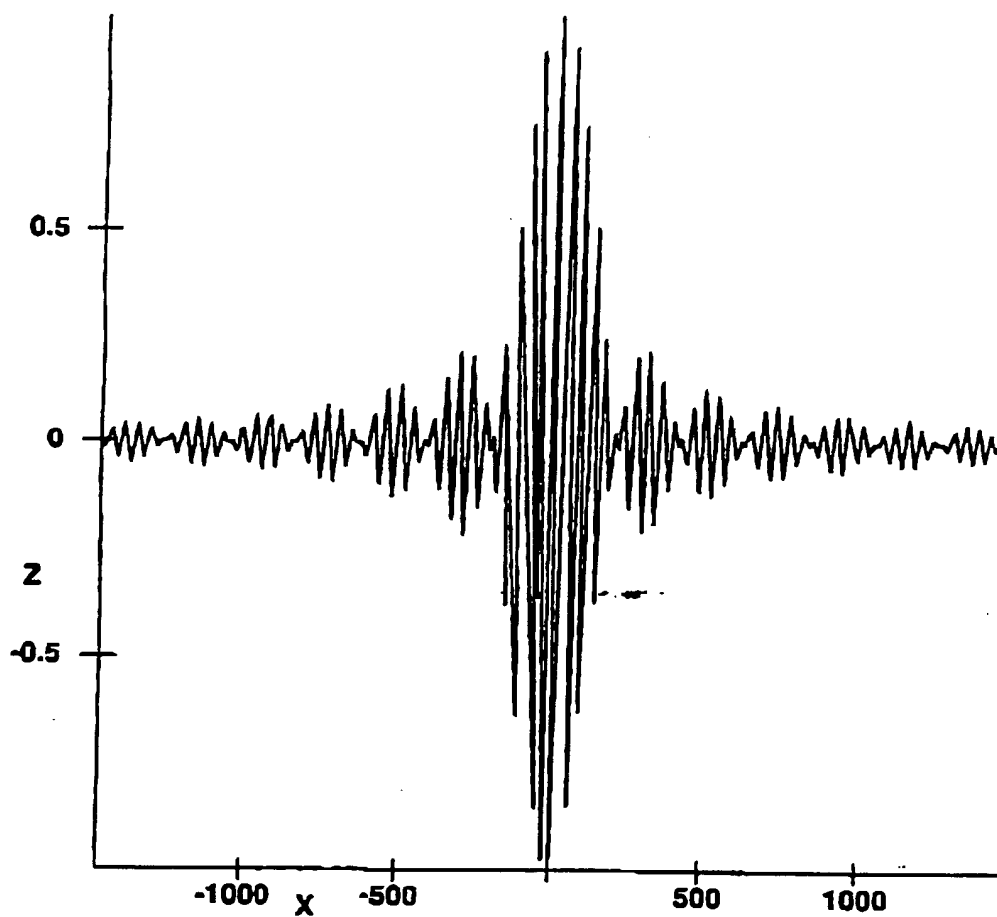
FIG. 5
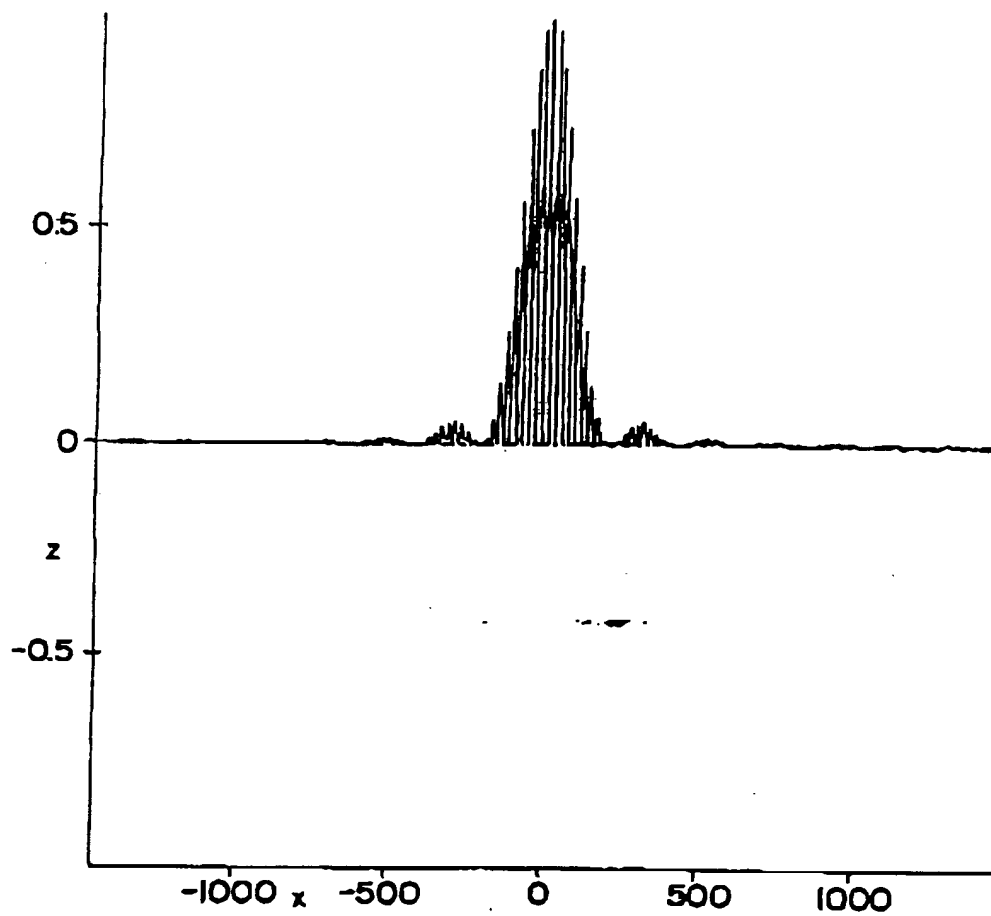
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FIG.6

Grating envelope: 1 lobe on each side of central peak

Wavelength (um)
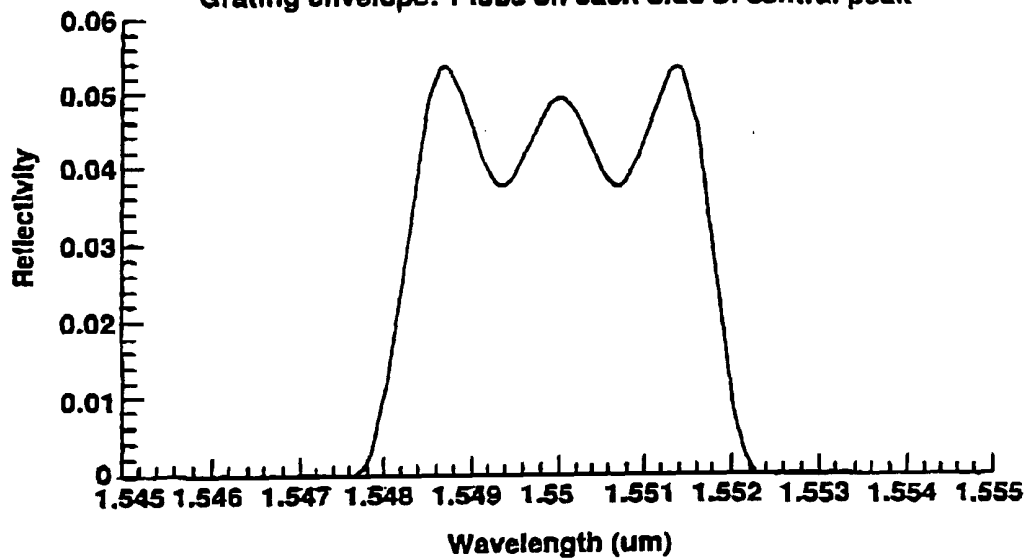
FIG.7

Grating envelope: 3 lobes on each side of central peak

Wavelength (um)
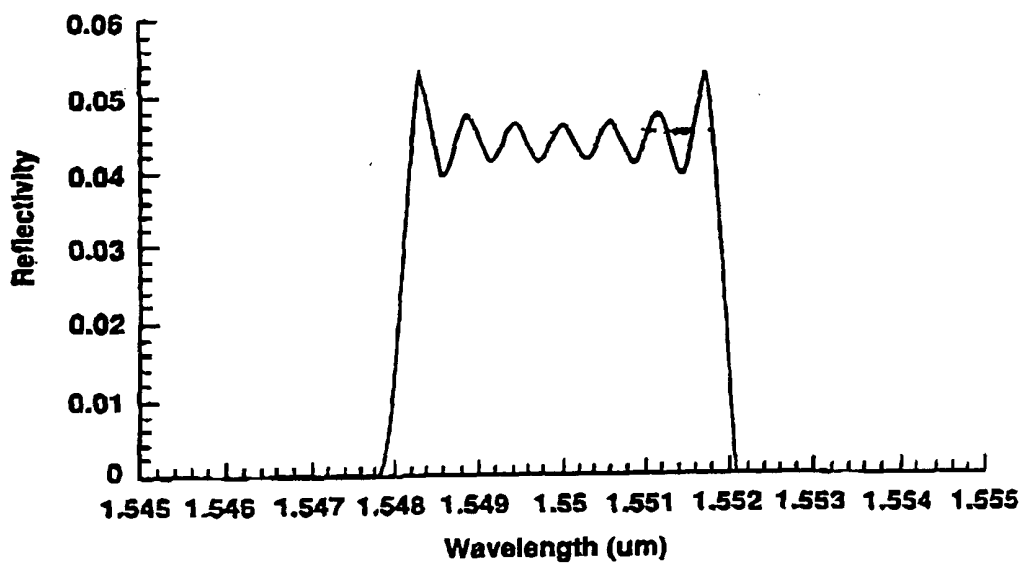
FIG.8

Grating envelope: 6 lobes on each side of central peak
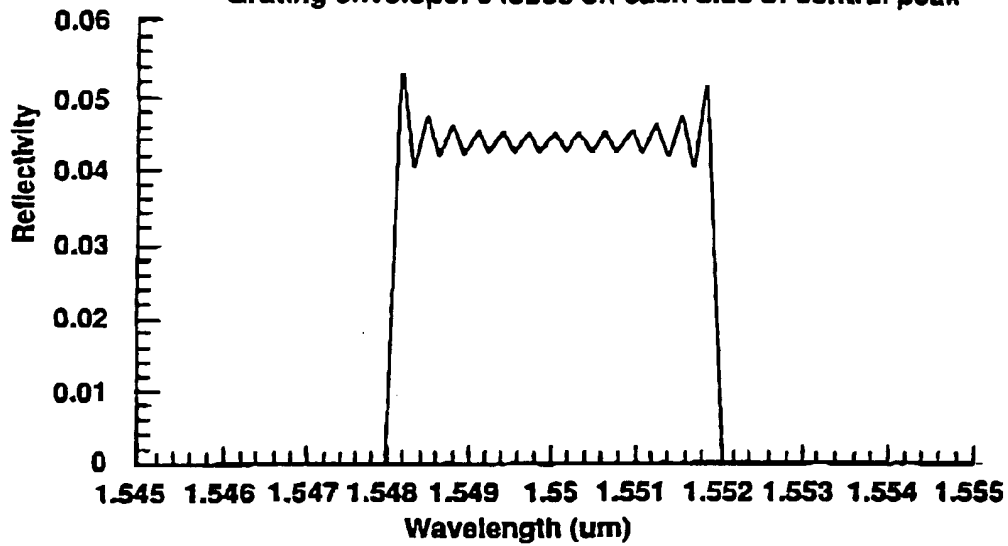
FIG.9

Grating envelope: 12 lobes on each side of central peak
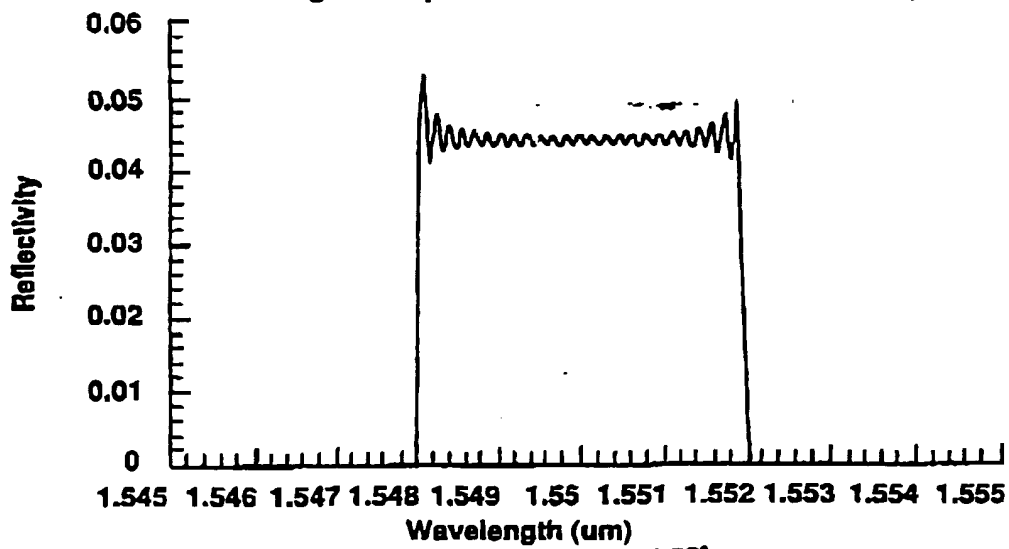
FIG.10

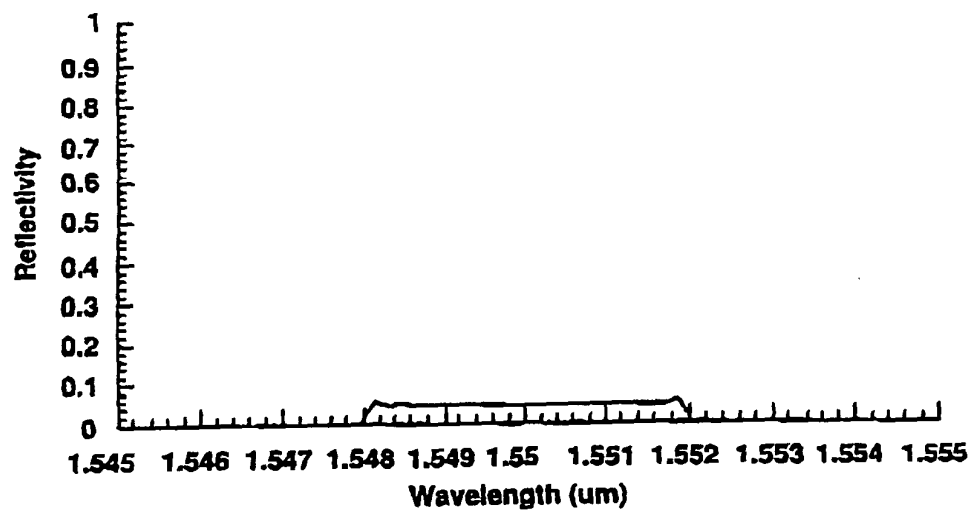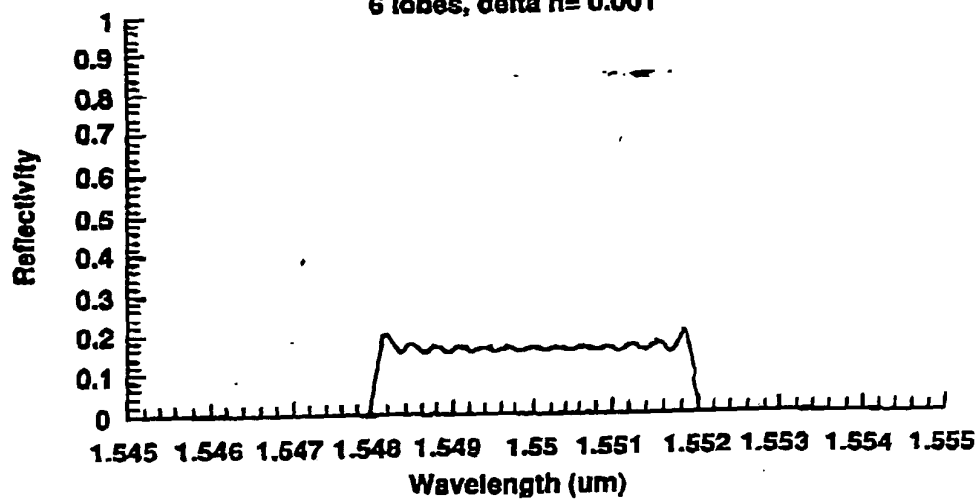6 lobes, delta n= 0.0005

FIG.11

6 lobes, delta n= 0.001

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FIG.12

6 lobes, delta n = 0.002

FIG.13

6 lobes, delta n = 0.005
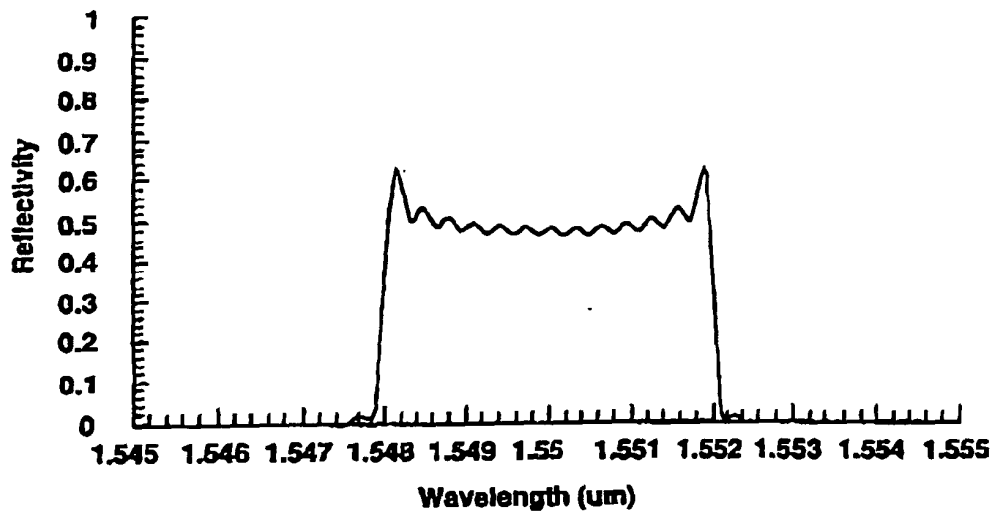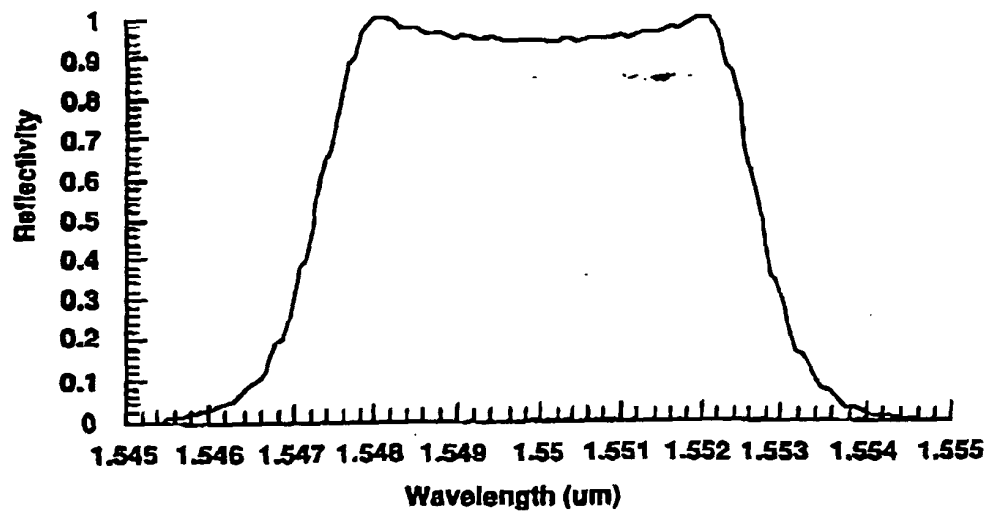
INTERNATIONAL SEARCH REPORT

International application No.
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A.   CLASSIFICATION OF SUBJECT MATTER
IPC(6)   : GO2B 6/26, 6/42; 6/32, 6/34; GO2B 5/18, 27/44
US CL   : 385/ 31, 333, 35, 36, 37; 359/ 566, 572
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B.   FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   385/ 31, 333, 35, 36, 37; 359/ 566, 572

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
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C.   DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,066,133 A (BRIENZA) 19 November 1991, see whole document.	1-23
Y	US 5,377,288 A (KASHYAP et al) 27 December 1994, see whole document.	1-23
Y	US 5,351,321 A (SNITZER et al) 27 September 1994, see whole document.	1-23
Y	US 5,367,588 A (HILL et al) 22 November 1994, see whole document	1-23

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

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